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Testing of a new morphing trailing edge flap system on a novel outdoor rotating test rig

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Abstract

The morphing trailing edge system or flap system, CRTEF, has been developed over the last 10 years at DTU Wind Energy. After a promising wind tunnel test of the system in 2009 the INDUFLAP project has been carried out from 2011-2014 to transfer the technology from laboratory to industrial manufacturing and application.
To narrow the gap between wind tunnel testing and full scale prototype testing we developed the rotating test rig. The overall objectives with the rotating test rig are: 1) to test the flap system in a realistic rotating environment with a realistic g-loading; 2) to measure the flap performance in real turbulent inflow and 3) to test the flap system in a realistic size and Reynolds number when comparing with full scale applications..
The rotating test rig consists of a 2.2m blade section attached to a 10m boom and mounted on a 100kW turbine platform. It was installed in June 2014 and a short measurement campaign was conducted in the autumn 2014.
An important result of testing the flap system on the rotating test rig was operation of the flap system up to 30 rpm. which a g-loading of 9-10g comparable with the conditions on a 2-3MW turbine.
Another important result was the measured performance of the flap system. We found that about 5.0deg. flap angle gives the same load change as 1deg. pitch. This is somewhat lower than simulations have shown which are in the range of 2 to 3 deg. flap angle to 1deg. pitch angle for a 15% flap. The realistic, turbulent inflow is probably a major cause of this lower performance.

Keyword

CRTEF: Controllable Rubber Trailing Edge Flap
Flap testing
Morphing airfoil
Rotating test rig
Pressure measurements

1. Introduction

Considerable research on SMART blade technology has been conducted for more than 10 years and has shown big potentials for load reduction on MW turbines using distributed control for alleviation of the fluctuating loads along the blade span [1]. However, the requirements by the wind turbine industry of robust actuator solutions where the strongest specifications mean no metal and electrical parts in the blades have so far limited the use of the smart blade technology on wind turbines.
The development and testing of the morphing trailing edge flap system to be presented in the present paper, also called the Controllable Rubber Trailing Edge Flap (CRTEF), was initiated in 2006. The first prototype was tested in the laboratory in 2008 and in late 2009 wind tunnel measurements in the Velux wind tunnel in Denmark were conducted on a blade section of 1.9m span and 1m chord with a 15% trailing edge flap system [2]. From 2011 to 2014 the INDUFLAP project, funded by the Danish national funding board EUDP, was conducted with the overall aim to transfer the technology from laboratory conditions to industrial manufacturing and application [3]. An important part of this work was the testing of the flap system on an outdoor rotating test rig in order to reduce the gap in test conditions between wind tunnel testing and full scale testing on a MW turbine.
In the present paper the developed flap technology will first be briefly described. Then the design and construction of the rotating test rig will be presented followed by a section with results from a few weeks test campaign in the autumn 2014

2. The developed flap technology – the CRTEF system

2.1 The flap actuation concept

The initial flap concept studies back in 2006 led to the design of the so-called Controllable Rubber Trailing Edge Flap (CRTEF) which comprises a morphing trailing edge manufactured in an elastic material with a number of voids inside. Their geometry are designed so that pressurizing some or all of the them will create a deflection of the flap.
In an actual design shown in Figure 1 the

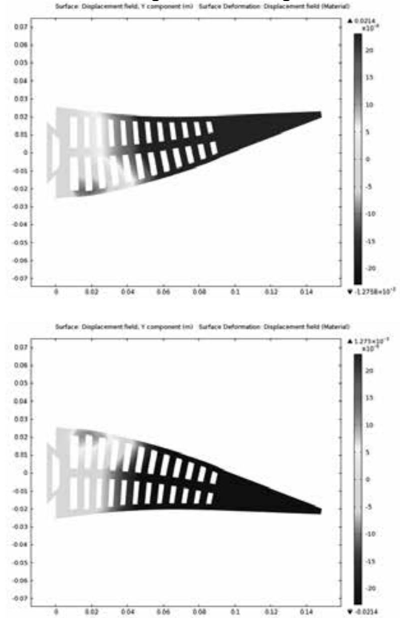

Figure 1 – Deflection of the flap by pressurizing the lower and upper layer of voids, respectively.

voids are orientated in the spanwise direction in two layers which is a design suited for manufacturing by extrusion. Pressurizing the lower layer will give an upward deflection as shown in the upper part of Figure 1. Likewise, pressurizing the upper row of voids will give a downward deflection as shown in the lower part of Figure 1.

2.2 Flap design and manufacturing

During the above mentioned INDUFLAP project carried out by DTU Wind Energy in cooperation with the two industrial partners Hydratech and Rehau a flap design well suited for manufacturing in an extrusion process was developed. It consist of three main parts; a passive, load carrying part as shown in Figure 2 and two actuation parts containing the voids as shown in Figure 3 where they are assembled with the passive part.

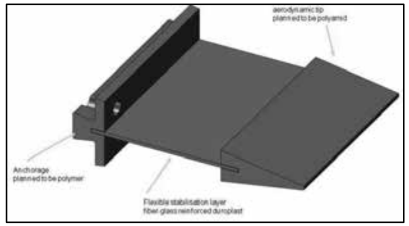

Figure 2 – The passive, load carrying part of the flap system.

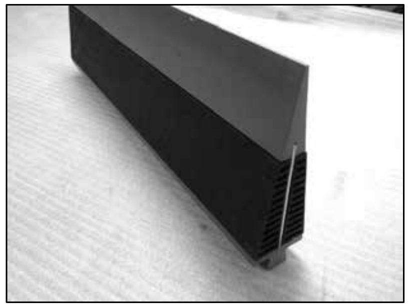

Figure 3 – The two actuation flap elements assembled with the load carrying part.

The manufacturing of the 2m long actuation parts was performed by Rehau in a continuous thermoplastic extrusion process in form of a quasi endless 12 chamber hollow profile using the santoprene material. For manufacturing the sealed ends of the hollow profiles, a special method of a contact welding process was developed.

2.3 Flap integration into the blade and overall blade design

The integration of the flap system into the blade is an important part of the concept. It should allow an easy mounting of the flap so that a possible replacement of the flap segments can be carried out without any heavy tools and equipment. If a spanwise length of e.g. 3m is chosen it should be possible for two technicians climbing on the blade to dismantle a flap segment and mount a new one. Further, if the extrusion process is used for manufacturing the flaps, they will have a constant chord. It is therefore proposed to use different sizes of flaps along the blade span with passive, 3D mold manufactured flaps in between to enable a more continues blade planform. By passive flaps are meant flaps that don´t have voids and they can therefore easily be manufactured in a full 3D geometry, e.g. by a molding process, with variable chord length so they can be inserted between the active flaps with constant chord and thus give a smoother planform distribution.
One overall blade design could therefore be a blade manufactured without the last about 10% of the trailing edge region along the whole span. On the inboard part of the blade with the thick airfoils this would form the flat back airfoils commonly used to improve aerodynamic performance of thick airfoils.
From e.g. 1/3 of the radius and to the tip, passive and active flap sections could then be mounted. During the INDUFLAP project [3] the attachment elements shown in Figure 4 were developed. A big advantage of the design is that it will reduce the requirements for blade trailing edge finishing a lot as the rest material from the gluing does not need to be removed. It also enables a fast attachment of the flap to the blade and in the lab. it took less than a minute to mount the 2m flap on a blade section as shown in Figure 5.

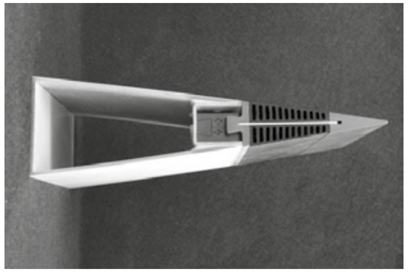

Figure 4 – The flap attachment to the blade.

Figure 5 – Demonstration in the lab. of mounting the 2m flap on a blade section.

3. The rotating test rig

At an early stage of development of the flap system wind tunnel tests were carried out in 2009 to verify the aerodynamic response characteristics of the system [1]. Pressure measurements were carried out on a blade section of 1.9m span, 1m chord and with a 15% CRTEF system in the VELUX wind tunnel in Denmark. The unsteady aerodynamic response characteristics were derived showing a characteristic time constant of about 100ms.
However, there is big step from wind tunnel testing on a stationary blade section to full scale turbine application and therefore a so-called rotating test rig has been developed in the INDUFLAP project [3].

The idea behind the test rig is that the testing should be as close as possible to the rotating environment on the real turbine. So exposing the flap system to a g-loading comparable with the conditions on the fullscale turbine is one of the main objectives but also measuring the flap performance in unsteady inflow conditions as on the real turbine operating in the atmospheric boundary layer is another important aim. Finally it is desirable that the size of the flap is not that far from full scale.
It is expected that testing the flap system on the rotating rig will reduce the time for prototype testing on a full scale turbine where the costs for a test hour are several times bigger than for a test hour on the rotating test rig.

3.1 Rotating test rig design

To fulfill the above requirements to the test set-up we designed the rotating test rig comprising: 1) a blade section of 2.2m span and about 1m chord with aerodynamic shaped end caps; 2) a 10m pitchable boom where the blade section is attached to the one end and a counterweight at the other end and 3) a turbine platform where the boom is mounted on the shaft instead of a normal rotor, Figure 6.
The basic platform for the rotating test rig is the 100kW Tellus turbine positioned at the old turbine test site at DTU, Campus Risoe. The original three bladed rotor has been taken down, Figure 7 and a new 100kW full

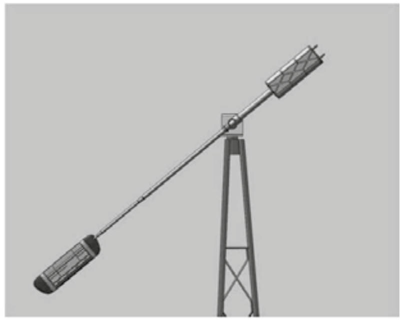

Figure 6 – Sketch of the rotating test rig.

variable speed drive was installed so the rotational speed with the boom mounted is controllable between 0 and 60 rpm.

Figure 7 – The 100kW Tellus turbine is used at the platform for the rotating test rig.

3.2 Blade section design and manufacturing

The blade section has the NACA0015 aerofoil shape and a constant chord length of 1m. The overall concept consists of a spanwise 2.2 meter long wing section covered with side pods in each end giving a total length of 3.4 meter. The blade section is built up on an inner aluminum structure covered with two shells of glass-epoxy composite material, Figure 8 and Figure 9. The aluminum structure consists of an 110mm hollow tube, two rib structures and a U-profile web. The aluminum parts were welded together.
The tube makes it possible to mount and dismount the wing section on a boom and the U-profile web at the trailing edge is for fixation of different morphing flap systems.

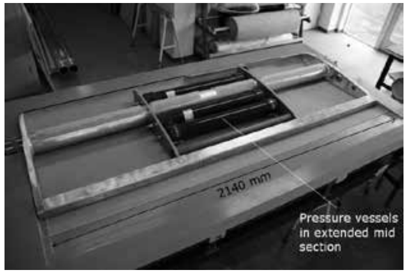

Figure 8 – The inner aluminium structure of the blade section.

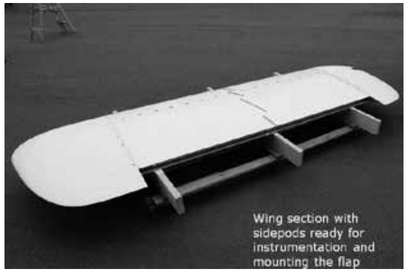

Figure 9 – The blade section ready for instrumentation and mounting the flap system.

3.3 Boom design and installation

The boom is built up of four thin-walled tubular sections (three of aluminium alloy 6082 and one of steel St52) and the connection pieces and flanges between them, Figure 10. The blade section is attached with a 100mm diameter rod sliding into the tube in the blade section Figure 8.

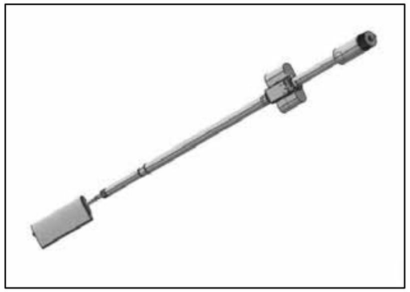

Figure 10 – The boom design.

The boom is fully pitchable so that a combined pitch and flap control can be investigated.
The boom with the blade section and flap system was installed in June 2014, Figure 11, and the test rig was ready for measurements in September 2014, Figure 12.

Figure 11 – Installation of the boom and blade section in June 2014.

Figure 12 – Rotating test rig ready for measuring.

3.4 Pneumatic system for flap actuation

Pressurizing the voids can be done either by a hydraulic or a pneumatic system or by a combination of the two systems. The choice of system depends e.g. on the requirements for the actuation time constant and on how strong the restrictions are on having valves/wires in the blade.
In the present case a first option has been a pneumatic system developed and implemented by Hydratech Industries which were one of the industrial project partners in the INDUFLAP project.
A compressor at the hub supplies pressurized air into 3 accumulators which are the black tubes mounted in the blade section shown in Figure 8. They have three different pressure levels: low, medium, and high. A series of 3 switches per flap side ('positive'-upper, negative'-lower) control which of the three pressure levels is connected to the flap voids (on-off). A fourth switch per flap side controls the release of pressure. Controlling the switch valves allows for dynamic control of the pressure in the voids and therefore the flap deflection. The pressure at the flap inlets, the switches, the accumulators and the compressor are measured using pressure transducers.

3.5 Instrumentation

Besides the advantages by the rotating test rig mentioned above, one other major advantage by testing the flap system on a blade section is that it is possible to install a surface pressure measurement system which would be very complicated to implement on a full scale blade. By measuring the pressure distribution, the instantaneous aerodynamic loading can be derived and the performance of the flap system investigated.
The installed pressure system comprised 59 pressure holes distributed along the chord at the mid span position and additional 16 pressure taps at the 25% chordwise position to monitor the spanwise load distribution. The pressure taps were connected to two 64 channel Scannivalve pressure scanners mounted inside the blade section.

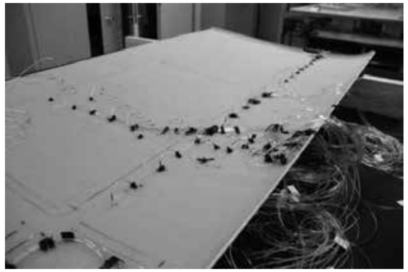

Figure 13 – Pressure taps installed on the suction side at the mid span position and along the span at 25% chord from the leading edge.

Besides the pressure measurements several accelerometers and strain gauges were mounted on the boom and the nacelle. In order to correlate the pressure measurements to the unsteady inflow, two five hole pitot tubes were mounted on the leading edge with the sensor head about ½m in front of the leading edge, Figure 14. A meteorology mast was positioned about three rotor diameters west of the test rig where wind speed and direction was measured in several heights. In total, 196 data channels are recorded.

Figure 14 – The blade section with the CRTEF flap system. Inflow measured with two five hole pitot tubes.

3.6 Calibration of the flap deflection correlated to actuation pressure

It was not possible to measure the flap deflection directly with a sensor (e.g. a strain gauge built into the flap) on the rotating test rig and therefore a calibration in the lab. correlating the flap deflection to the pressure in the voids has been used. The calibration set-up shown in Figure 15 was used. A laser sensor measured the flap deflection and the supply pressure in the two layers of voids was likewise measured. An example on how the flap deflection correlates with the pressure is shown in Figure 16. It is seen that there is a close correlation between pressure and deflection although there might be minor hysteresis effects.
The result of the calibration was 1.85 deg./bar to the one side and 1.48 deg./bar to the other side.

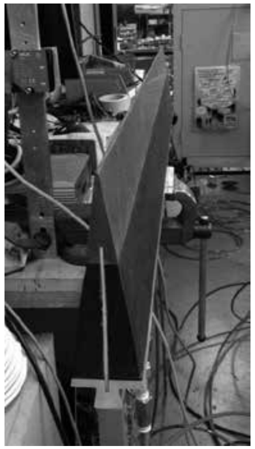

Figure 15 – Set-up for calibrating the flap deflection correlation to pressure in the voids.

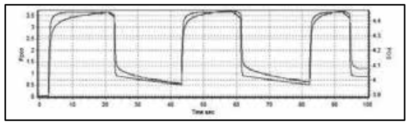

Figure 16 – Example of flap deflection calibration correlating the activation pressure (blue curve) to the flap deflection (red curve – [Volt]).

4. Experimental results

An important result of testing the flap system on the rotating test rig was operation of the flap system up to 30 rpm. which combined with a 10m radius gives a g-loading of 9-10g which is the same range as the system will be exposed to on a 2-3MW turbine.
Then during the relative short measurement period that was available for the first measurement campaign on the rotating test rig in the autumn 2014 the focus was on characterization of the flap performance using prescribed flap variations. An example is showed in Figure 17 where the flap angle was changed with 10 deg. each

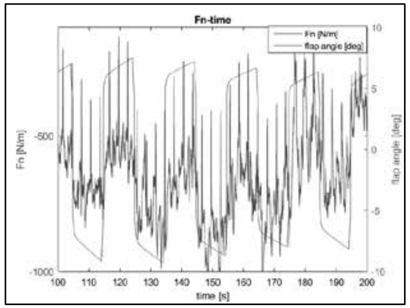

Figure 17 – The normal aerodynamic load force on the blade section (blue curve) for a flap angle variation of total 10 deg. (red curve) each 10 sec.

10s. The aerodynamic normal force integrated from the measured pressure distribution is seen to change with the flap angle. The unsteadiness in the inflow due to the turbulence and tower shadow is also clearly seen in the aerodynamic loading. This makes the visibility of the flap action more unclear. It should be noted that the tower shadow is quite strong in this case due to downwind operation of the rotor during this particular test.
One way of characterizing the flap performance was carried out in the following way. A few 10min. time series were measured at a constant rotational speed of 20 rpm. with a square change pattern of the flap angle with a period of 10s. as shown in Figure 18. The flap angle variation was not completely symmetrical around 0deg. but the mean total amplitude was around 15deg when using the time sequencies marked with red and blue, respectively, in Figure 18. To achieve a wide range of inflow angles the pitch setting was changed from one 10min. time series to the next.
The normal force loading was derived from the pressure data and then binned on the measured inflow angle derived from the five hole pitot tube measurements, Figure 19. From that figure we can now derive that the average change in normal force due to a degree change in flap angle is about 32% of the average change in normal force due to a degree change in inflow angle.

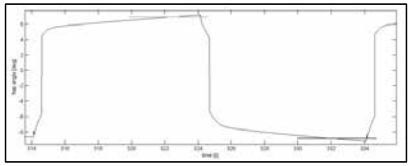

Figure 18 – A square pattern change of flap angle with a period of 10s.

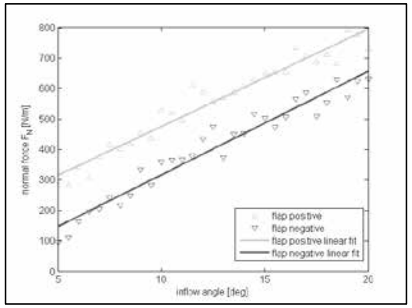

Figure 19 – Normal force data for extreme flap positions plotted against inflow angle. Data averaged every 0.5deg inflow angle.

The calibration and interpretation of the inflow angle is the uncertain parts of the above analysis. Another way of characterizing the flap performance would be to derive the lift and drag coefficients for different flap angles on basis of the measured aerodynamic loading from the pressure measurements and using the inflow angle and the relative velocity from the five hole pitot tube to derive these non-dimensional coefficients. However, this is not a straight forward data reduction for turbulent, unsteady inflow data and in particular due to the low aspect ratio of the blade section and how this influence the local inflow angle.
Therefore another measure of the flap performance is presented. Often we are interested in comparing the capability of the flaps to change the loading with the well known control by pitching the whole blade section.
The result of this analysis is shown in Figure 20 where the normal force is plotted for a number of different pitch settings and again for the same data set as used in Figure 19
The data show a considerable scatter due to the changes in wind speed but deriving the mean normal force for the different pitch settings a clear effect of the flaps are seen. From these mean data we can derive that the total about 15deg. change in flap angle gives almost the same change in aerodynamic loading as 3.0deg. change in pitch. This means that the lift change from about 5 deg. flap angle is the same as for one degree pitch.
This is somewhat less than simulations typically have shown which are in the range of 2 to 3 deg. flap angle to 1 deg. pitch angle for a 15% flap, Troldborg 2005 [4]. The turbulent, unsteady inflow is probably a major cause of this lower performance.

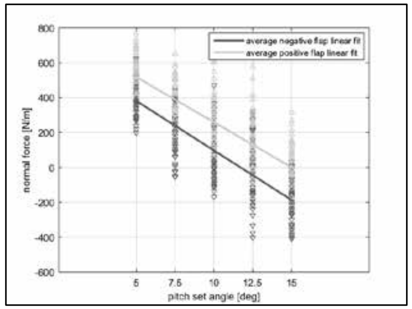

Figure 20 – the normal force on the blade section for plus/minus 5 deg. flap angle as function of the pitch setting of the flap angle.

5. Conclusion

The morphing trailing edge system or flap system, CRTEF, has been developed over the last 10 years at DTU Wind Energy. After a promising wind tunnel test of the system in 2009 the INDUFLAP project has been carried out from 2011-2014 to transfer the

technology from laboratory to industrial applications. During that work a flap design was developed where the manufacturing is done in an extrusion process using the santrophene material for one of the components.
To narrow the gap between wind tunnel testing and full scale prototype testing we developed the rotating test rig. The overall objectives with the rotating test rig are: 1) to test the flap system in a realistic rotating environment with a realistic g-loading; 2) to measure the flap performance in real turbulent inflow and 3) to test the flap system in a realistic size and realistic Reynolds number.
The rotating test rig consists of a 2.2m blade section attached to a 10m boom and mounted on a 100kW turbine platform. It was installed in June 2014 and a short measurement campaign was conducted in the autumn 2014. Instantaneous aerodynamic loading in a cross section of the blade was derived from pressure measurements providing detailed insight into the unsteady flap response.
An important result of testing the flap system on the rotating test rig was operation of the flap system up to a 30 rpm. which combined with a 10m radius gives a g-loading of 9-10g which is comparable to the conditions on a 2-3MW turbine.
Another important result was the measured performance of the flap system. As the blade section has a low aspect ratio we have chosen to compare the flap load response with the pitch load response as the pitch is the normal control system. We found that about 5 deg. flap angle gives the same load change as 1 deg. pitch. This is somewhat less than simulations have shown in the past which are in the range of 2 to 3 deg. flap angle to 1 deg. pitch angle for a 15% flap. The realistic, turbulent, inflow is probably a major cause of this lower performance.

Acknowledgements

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